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RESEARCH PAPER

Giant Induan oolite: A case study from the Lower Triassic Daye Formation in the western Hubei Province, South China

Mingxiang Mei [a,b,*], Jinhan Gao [b]

[a] *State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing 100083, China*
[b] *School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China*

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Abstract Most Phanerozoic oolites are marked by ooids with a diameter less than 2 mm. Observations on a Neoproterozoic oolite have resulted in a change of concept. The term “pisolite” that traditionally referred to oolites with a grain size of more than 2 mm, is now restricted to those coated carbonate grains formed by meteoritic freshwater diagenesis; oolites with a grain size of more than 2 mm are now defined as “giant”. Particular unusual giant oolites within a set of oolitic-bank limestones with thicknesses of more than 40 m in the top part of the Lower Triassic (Induan) Daye (Ruiping) Formation at the Lichuan section in the western part of Hubei Province in South China, represent an important sedimentological phenomenon in both the specific geological period and the geological setting that is related to the end-Permian biological mass extinction. Like the giant oolites of the Neoproterozoic that represent deposits where oolites formed in a vast low-angle carbonate ramp at that special geological period, the Triassic Daye Formation at the study section are significant because they provide a comparative example to help understand the evolving carbonate world reflected by oolites, the origin of which is still uncertain,

* Corresponding author. State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing 100083, China. Tel.: +86 13701326033.
E-mail address: meimingxiang@263.net (M. Mei).

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and they give insight into the sedimentation pattern of the desolate sea floor, which resulted from the mass extinction at the turn of the Permian into the Triassic.

1. Introduction

Oolites are marked by both an even lamination of the oolitic cortex and the general absence of biogenic features; they are distinct from oncolites, which are another type of coated carbonate grains (Tucker and Wright, 1990; Mei et al., 1997; Siewers, 2003). The smooth rings of the oolitic cortex are probably the most reliable criterion to distinguish oolites from oncolites, and biogenic features such as mucus films are evident in many oolites (Newell et al., 1960; Flügel, 2004). There is a clear but arbitrary size distinction between oolites and pisolites, with the term oolite referring to grains smaller than 2 mm and pisolites being those oolitic grains larger than 2 mm. However, the term “pisolite” is also used by many sedimentologists to refer to nonmarine oolite-shaped grains that are formed by meteoric fresh-water diagenesis (e.g. Flügel, 2004). Observation on and detailed study of the ‘giant’ oolites in the Neoproterozoic have led to a change in the usage of these terms (Summer and Grotzinger, 1993; Grotzinger and James, 2000), so that now the term giant oolite refers to large (>2 mm) oolitic grains formed in a marine environment (Siewers, 2003; Flügel, 2004).

In general, recent oolites tend to be less than 1 mm in grain size (Tucker and Wright, 1990; Mei et al., 1997; Siewers, 2003). Although there are some exceptions, most oolites throughout the Phanerozoic have grain sizes smaller than 2 mm. Archean and Proterozoic oolites tend to be slightly larger but are still predominantly less than 2 mm in grain size (Grotzinger and James, 2000). So far, giant oolites that have been described and studied are preferably developed in the Neoproterozoic (Summer and Grotzinger, 1993; Grotzinger and James, 2000). For a set of oolitic-bank limestones that is developed in the top part of the Triassic Daye Formation (or the Ruiping Formation of the Dye Group; Chen and Jin, 1997; Yang et al., 2000) at the Lichuan section in the western part of Hubei Province, South China (see Fig. 1), most of ooids have a grain size of more than 2 mm and represent a particular giant oolite occurrence in the Phanerozoic. These oolitic limestones formed during a special geological period, i.e., the Induan, and in a special sedimentary setting, i.e., on a ramp carbonate platform after a major transgression and severe biological mass extinction at the turn of the Permian to Triassic in South China (Chen, 1995; Hallam and Wignall, 1999; Mei and Tucker, 2007; Mei et al., 2007). Thus, similar to the giant oolites of the Neoproterozoic (Summer and Grotzinger, 1993; Grotzinger and James, 2000), several features, which include the special forming geological time period, the special sedimentary setting, and the unusual appearance of giant oolites throughout the Phanerozoic in general, endow the Triassic giant oolites in the study area with an important sedimentological significance.

2. Geological background

In South China, oolitic limestones are well developed in the Triassic (Induan) Daye Formation (Fig. 1); the Daye Formation is equivalent to the Ruiping Formation of the Daye Group (Wu et al., 1994; Chen and Jin, 1997; Yang et al., 2000). According to the studies of Wu et al. (1994), the carbonate strata with the development of oolitic limestones that are defined as the Daye Formation are distinct from the littoral strata made up of sandstones and mudstones of the Induan Feixianguan Formation in the western part of the Upper Yangtze region close to continental areas. Wu et al. (1994) have also demonstrated that the oolitic-grained bank underwent a progradation process toward the east throughout the Induan age. With this special background, a set of oolitic-bank limestones with a thickness of about 50 m were developed in the top part of the Daye Formation at the Lichuan section in the western part of Hubei Province (Fig. 2).

According to the international stratigraphic standard (Chen and Jin, 1997; Yang et al., 2000; Gradstein et al., 2004; Zhang et al., 2009), the duration of the Induan is from 251.0 ± 0.4 Ma to ~249.5 Ma. At the Lichuan section, the Ruiping Formation is

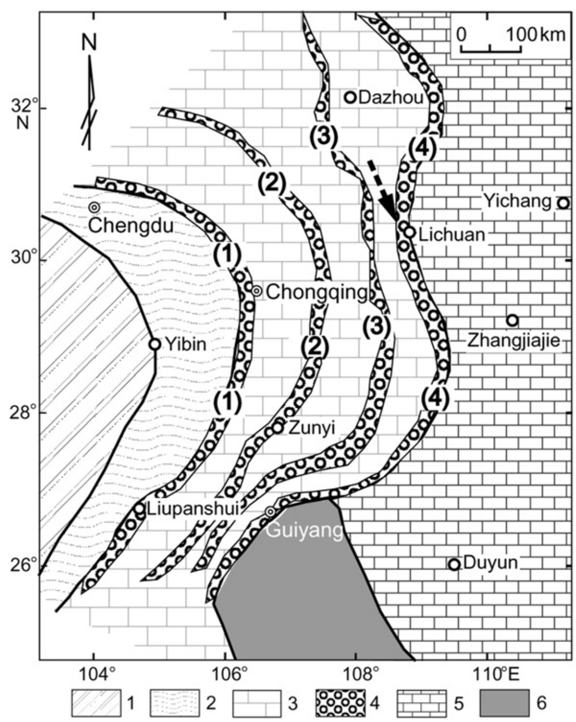

Figure 1 Simplified map showing Induan (Early Triassic) paleogeography and sedimentary facies of the Upper Yangtze region and the location of the studied section (arrowed). Lithofacies codes are: 1 = nearshore sandstone; 2 = offshore sandstones and mudstone; 3 = shallow-ramp limestone; 4 = oolitic-bank limestone; 5 = middle- to deep-ramp limestone; 6 = shelf to basin marl and shale. (1) to (4) = developing periods of oolitic bank throughout the Induan (proposed by Wu et al., 1994). Siliciclastic facies, 1−2 = Feixianguan Formation, carbonate facies; 3−5 = Daye Formation, shelf facies; 6 = Luolou and Qingyan formations. The south is part of the Dianqiangui or Nanpanjiang Basin (Mei and Tucker, 2007; Mei et al., 2007).

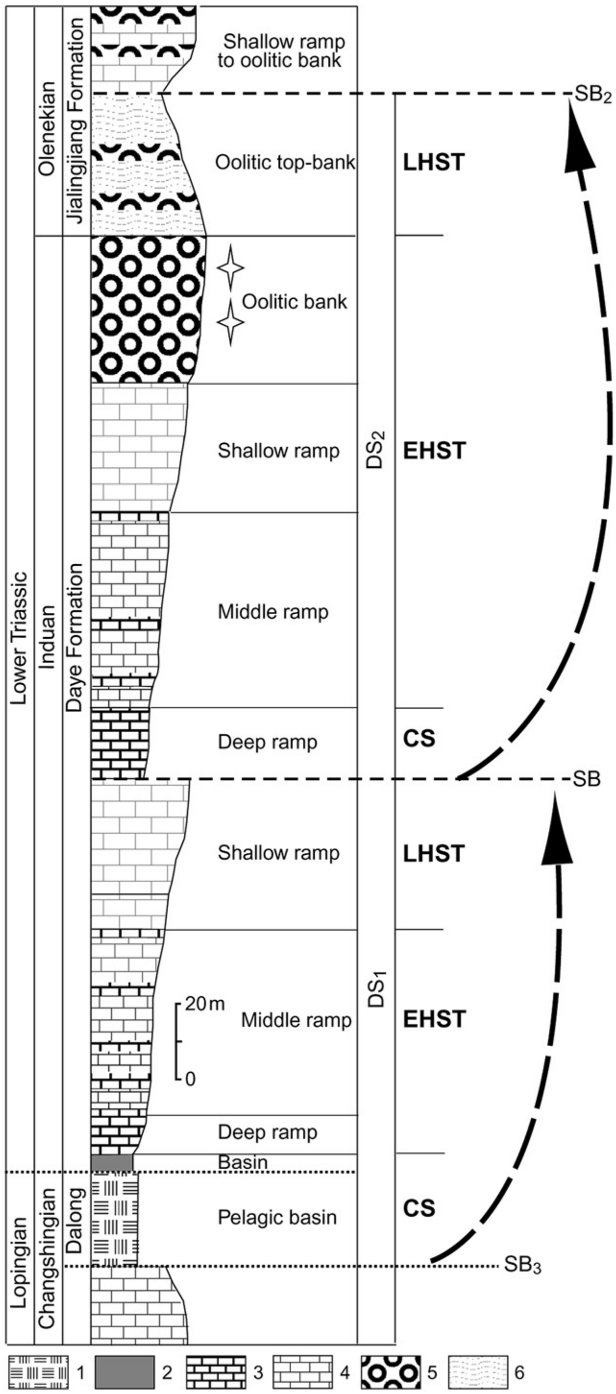

Figure 2 Log showing the sequence-stratigraphic division for the Lower Triassic Daye Formation at the Lichuan section, Hubei Province, South China. DS_1 and DS_2 refer to two third-order sequences discerned from the Permian Dalong Formation thru to the lower part of the Triassic Jialingjiang Formation at the Lichuan section. SB = sequence boundary of transitional type; SB_2 = type II; SB_3 = drowning-unconformity type of sequence boundary. Compositional units for third-order sequences are: CS = condensed section, EHST = early high-stand system tract, LHST = late high-stand system tract. Lithofacies codes are: 1 = siliceous rock; 2 = black shale; 3 = medium- to thin-bedded micrite; 4 = medium- to thick-bedded aphanitic micrite; 5 = oolitic grainstone; 6 = dolomite and dolomitic limestone. Stars represent the stratigraphic position of the oolitic limestone. The section location is the same as that as shown in Fig. 1.

marked by a set of limestones with some oolitic grainstones in its upper part. Long-term research on the paleontology has provided good chronostratigraphical control for the Daye Formation (Chen and Jin, 1997; Yang et al., 2000) in the Induan, which includes biostratigraphic zonations as follows: 1) bivalve zones from the lower to the upper, i.e. *Towapteria scythicum*, *Pseudoclaraia wangi*, *Claraia aurita* and *Eumorphotis multiformis* zones; 2) ammonite zones from the lower to the upper, i.e. *Ophiceras-Lytophiceras*, *Gyromites-Prionolobus*, *Koninckites-Xenodiscoides* and *Plemingites* zones; and 3) conodont zones from the lower to the upper, i.e. *Hinduodus minutus*, *Isarciella isarcica*, *Neogondollella carinata*, *Neospathodus dieneri*, *Neospathodus peculiaris* and *Neospathodus pakistanensis* zones. Furthermore, this set of oolitic-bank limestones was formed in the latest period of the Induan age, which belongs to the product of the fourth period of oolitic-bank development in the Upper Yangtze region proposed by Wu et al. (1994), as shown (4) in Fig. 1.

Considering the sequence-stratigraphic division for the coeval strata in adjacent areas, together with the underlying Permian Dalong Formation and the overlying basal part of the Jialingjiang Formation, the Daye Formation at the Lichuan section can be subdivided into two third-order sequences, i.e., DS_1 and DS_2 (Fig. 2). The basic features of these sequences can be summarized as follows:

(1) The basal boundary of DS_1 equates to a clear drowning-unconformity, exhibited by basin siliceous rocks of the Permian Dalong Formation that lie directly over high-stand carbonates of the Upper Permian Changxing Formation (Schlager, 1989, 1999; Chen, 1995; Hallam and Wignall, 1999; Mei and Tucker, 2007; Mei et al., 2007); this larger-scale rapid transgression that occurred at the turn of the Permian to the Triassic, formed an upward-shallowing succession of sedimentary facies from basin to shallow ramp making up DS_1;
(2) An abrupt transfer boundary of sedimentary facies from shallow to deep ramp in the middle part of the Daye Formation forms the basal boundary of DS_2, which is marked by a transitional type of sequence-stratigraphic boundary as defined by Vail et al. (1977), and an exposure-punctuated surface formed in the lower part of the Jialingjiang Formation, which is similar to the type-II sequence-stratigraphic boundary defined by Vail et al. (1977), between which an upward-shallowing succession of sedimentary facies from deep ramp to top oolitic-bank constitutes DS_2. Consequently, a set of oolitic-bank limestones with a thickness of about 50 m makes up the early high-stand system tract (EHST), and a set of dolomites with some dolomitic limestones and few oolites belonging to the lower Jialingjiang Formation makes up a forced-regressive wedge system tract (or late high-stand system tract (LHST); Hunt and Tucker, 1992) of the third-order sequence DS_2.

3. Macroscopic features of the Triassic giant oolite

As seen in Fig. 3, for the thick-bedded to massive oolitic grainstones in the top part of the Daye Formation at the Lichuan section, the macroscopic features can be summarized as follows:

(1) Large-scale wedge-shaped cross bedding is developed within the oolitic grainstones;
(2) Ooids are arranged by denseness and those with a grain size of more than 2 mm are frequently concentrated on the

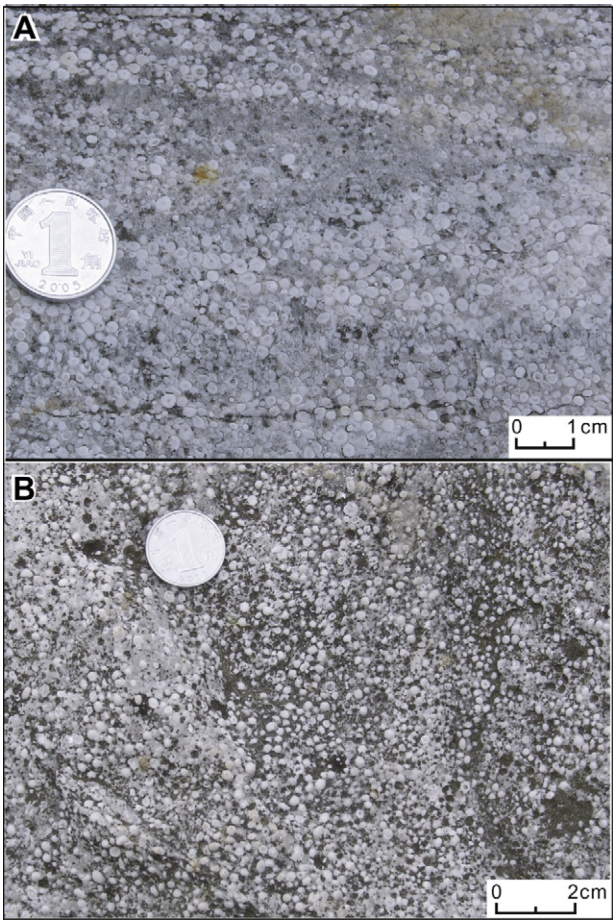

Figure 3 Photographs showing the macroscopic features for the Triassic oolites in the study area. Photo A demonstrates a giant oolite with dense distribution in the scouring surface and the development of large-scale cross bedding within the oolitic grainstone; Photo B exhibits ooids in three-dimensional view.

scouring surface (Fig. 3A); there are three-dimensional ooids visible in some parts of the outcrop in which some giant oolites are distributed (Fig. 3B);

(3) Some particular oolitic intraclastics resulted from the breakup of oolites caused by strong currents;

(4) Larger ooids with grain sizes of more than 2 mm (some from 4 to 5 mm) represent an unusual feature of giant oolites throughout the Phanerozoic, which are similar to those in the Neoproterozoic (Swett and Knoll, 1989; Summer and Grotzinger, 1993; Grotzinger and James, 2000; Mei, 2008).

Therefore, several features, such as the development of large-scale wedge-shaped cross bedding, the large thickness of a single bed that can be up to several meters (2–4 m), and the development of giant oolite and oolitic intraclasts, reflect the environment of formation for Triassic oolites at the Lichuan section in a high-energy agitating subtidal environment, i.e., the grain bank facies in the top part of the EHST unit of DS_2, as seen in Fig. 2.

4. Microscopic features of the Triassic giant oolite

Under the light microscope, there is a diversity of ooid morphologies for the oolite from the upper Daye Formation at the Lichuan section. The oolites are mainly composed of carbonate micrite (Fig. 4; see detailed description by Mei, 2008). Their microscopic features can be summarized as follows:

(1) Most of the ooids are circular (Fig. 4A and B), elliptical concentric (Fig. 4E), irregular eccentric (Fig. 4D), and some are composite (Fig. 4C). The ooid grain sizes are commonly more than 2 mm, with a few 4–5 mm; and the largest can be up to 7 mm (Fig. 4B and E);

(2) Many types of small carbonate grains, such as pellets (Fig. 4A and B), calcisiltite (Fig. 4C), echinoderm bioclast (Fig. 4E), silt-sized thrombolite with worm microscopic fabric (Fig. 4D) and particular ooid intraclast (Fig. 4C), make up the nucleus of the ooids. Furthermore, as seen in Fig. 4E, the echinoderm bioclasts that form the ooid nucleus have an obvious micritization feature in their exteriors margin that may be genetically related to microboring caused by euendolithic cyanobacteria (Chacón et al., 2006; Garcia-Pichel, 2006; Duguid et al., 2010), and these echinoderm bioclasts are coated by a micritic envelope in the form of a ring that is possibly formed by microbes;

(3) The ooid cortex is made up of even rings of dark micrite, which exhibit dark and light laminations;

(4) The thickness of the ooid cortex is always larger than the size of the nucleus, and the number of ooid rings is more than several tens, which reflects the basic feature of high-energy oolites;

(5) As seen in Fig. 4C, the nucleus of one large irregular-shaped composite ooid is made up of two small ooids, and this in turn is finally wrapped by even ooid rings, which result in a composite that is distinct from other aggregate grains such as grapestones and thrombolites; furthermore, this large composite reflects the basic feature of a rebirth ooid (Simone, 1981; Flügel, 1982, 2004; Tucker and Wright, 1990; Mei et al., 1997; Siewers, 2003);

(6) As seen in Fig. 4D, an eccentric ooid with a diameter of more than 3 mm indicates the basic feature of a rebirth ooid is similar to the feature reflected by a large irregular-shaped composite ooid seen in Fig. 4C, which may be the product of syndepositional deformation and a discontinuity during the growing process of the ooids (Simone, 1981; Flügel, 1982, 2004; Tucker and Wright, 1990; Mei et al., 1997; Siewers, 2003).

As seen in Fig. 5, the infillings of the ooids include cements of calcite spar and intraclasts. The various types of ooids shown in Fig. 4 probably belong to high-energy oolites (Simone, 1981; Flügel, 1982, 2004; Tucker and Wright, 1990; Mei et al., 1997; Siewers, 2003). The particular filling substances are those ooid intraclasts with clear ooid-ring microfabrics (Fig. 5A), which resulted from fragmentation and abrasion of oolites caused by strong currents during formation. For these calcite-spar cements (Fig. 5B), the first generation is marked by fibrous calcites, the second generation characterized by fibrous and flaky calcite, and the third generation is made up of equably grained blocky calcites with an obvious micropore about 0.1 mm across. Micropores within blocky calcite cements are partly concentrated in the central parts of pores among the ooids and are open through each other, which reflect obvious corrosion during diagenesis.

As mentioned above, the precise original mechanism of oolite formation is poorly understood. However, a number of processes have been put forward (Gerdes et al., 1994; Reid et al., 2000; Brehm et al., 2003, 2006; Duguid et al., 2010), which include: 1) biological formation, biological processes and organisms cause precipitation of calcium carbonate; 2) chemical formation,

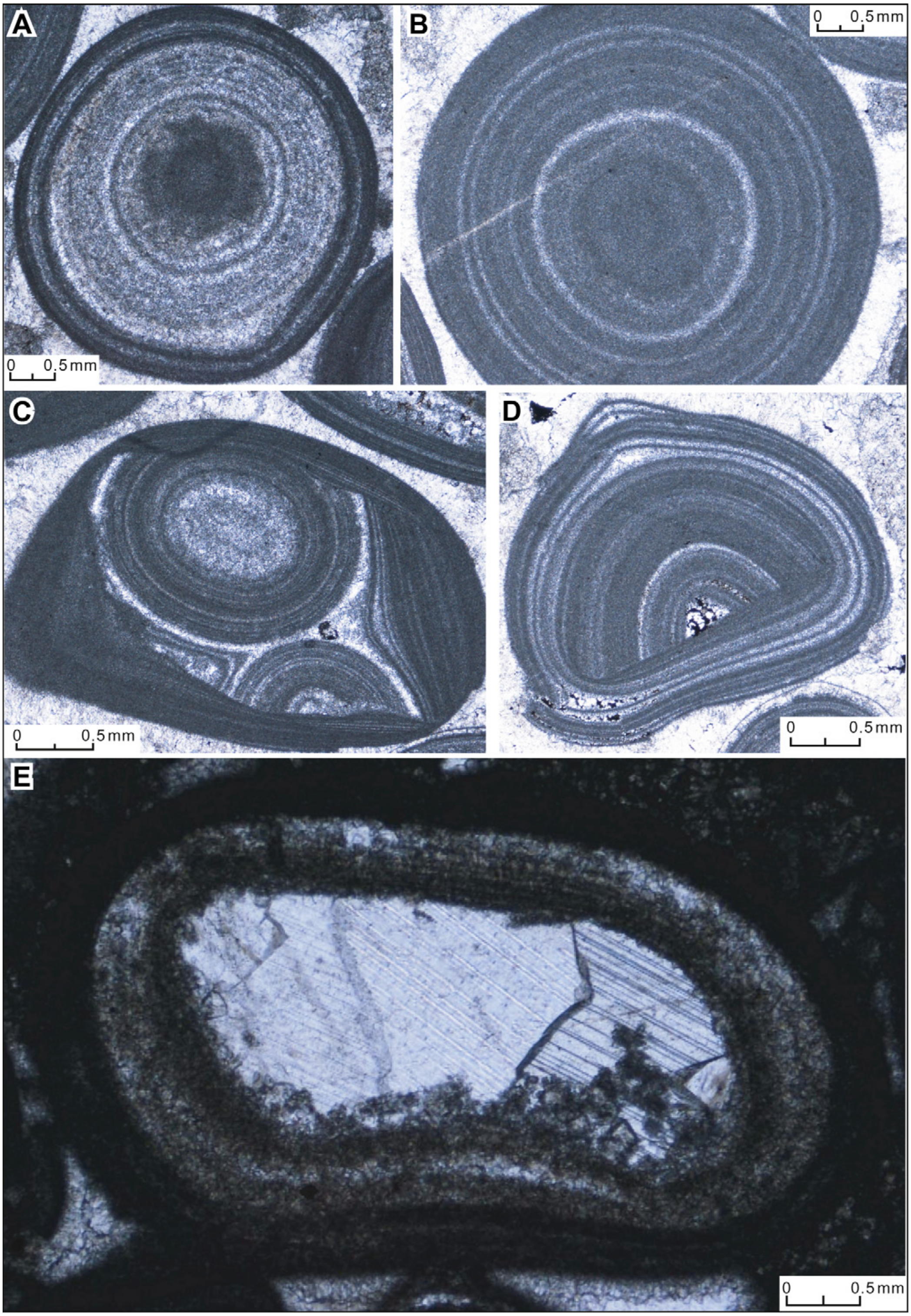

Figure 4 Images showing various giant oolite morphologies within the oolitic grainstones in the top part of the Triassic Daye Formation at the Lichuan section, Hubei Province. Images (A) to (B) are circular concentric ooids, (C) is a composite ooid, (D) is an irregular eccentric ooid, and (E) is an elliptical concentric ooid. All images were taken under plane-polarized light.

calcium carbonate is induced to precipitate around the nuclei when it supersaturates in an aqueous solution; 3) physical formation, through the accretion of calcium carbonate while the grain is being rolled around on the sea floor. It is likely, therefore, that a combination of these processes can be responsible for ooid formation, although microbial processes are emphasized by Gerdes et al. (1994) and by Brehm et al. (2003, 2006), and chemical processes by Duguid et al. (2010).

As seen in Fig. 4, the giant oolites of the Induan in the study area demonstrate a complex formation process that is related to

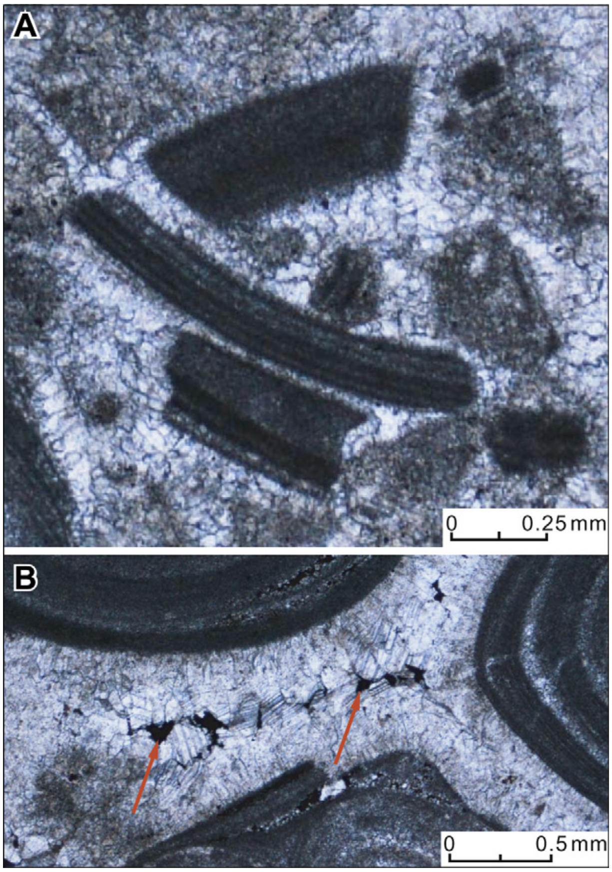

Figure 5 Images showing oolitic intraclasts (A) and multigenerational cements of calcite spar (B). A—shows angular oolitic intraclasts with a clear microscopic fabric to the ooid cortex; B— demonstrates the calcite spar cement within the inter-grain pores in which there are some clear micropores in the central part (arrowed). All images were taken under plane-polarized light.

the precipitation of amorphous calcium carbonate (ACC) caused by microbial activity. Firstly, as seen in Fig. 4A—D, the cortex of the ooids with various morphologies demonstrates dark and light laminations are similar to the basic feature of stromatolites, which may indicate that these oolites are the product resulting from a spherical microbial assemblage as proposed by Brehm et al. (2003, 2006). Secondly, some ooid rings are composed of dark amorphous micrites enriched with organic substances, as seen in Fig. 4, and this type of ooid ring has a thickness of several tens of microns that are similar to a micritic envelope, which demonstrates that the formation mechanism for this type of ooid ring is similar to the dark laminations of stromatolites and is genetically related to microbial activity. Thirdly, the basic feature of rebirth oolites as seen in Fig. 4C and D shows that the growth of the ooid rings might be controlled by a complex precipitation process of carbonate micrites that are genetically related to the activity of microbes, and this feature cannot simply be interpreted with the chemical formation process of carbonate micrites proposed by Duguid et al. (2010). Fourthly, as seen in Fig. 4E, the clear micritization feature in the exterior margin of an echinoderm bioclast that constitutes an ooid nucleus might be genetically related to a microboring caused by euendolithic cyanobacteria (Chacón et al., 2006; Garcia-Pichel, 2006; Duguid et al., 2010). Therefore, the formation mechanism for these oolites (e.g. Figs. 3 and 4) is directly or indirectly related to specialized microbial activity, as proposed by Gerdes et al. (1994) and Brehm et al. (2003, 2006).

5. Significance of Triassic giant oolites

Several features of the ooids within the Triassic oolitic limestones at the Lichuan section, i.e., the formation in the early high-stand period of third-order sea level change (DS_2 in Fig. 2; Tong et al., 1999), and during the progradational process of an oolitic bank toward the east depositing on a carbonate ramp (Fig. 1; Wu et al., 1994), the morphological diversity of ooids (Figs. 3 and 4), the special ooid intraclasts indicating abrasion and fragmentation during formation (Fig. 5A), and the multigenerational calcite spar cement (Fig. 5B), indicate that these oolites were generated in a high-energy subtidal environment (e.g., Reeder and Rankey, 2008). The Lower Triassic Daye Formation strata of the carbonate ramp at the Lichuan section formed in a shallower sedimentary environment than the outer platform paleoenvironment where the Induan Luolou Formation of the Nanpanjiang Basin was deposited (e.g., Galfetti et al., 2008). Although the environmental conditions for the formation of the oolitic grain remain uncertain (Simone, 1981; Flügel, 1982, 2004; Tucker and Wright, 1990; Mei et al., 1997; Siewers, 2003), the top Daye Formation oolitic grainstones reflect a favorable sedimentary background for the generation of oolites in the last part of the Induan.

The special conditions that are the key to the formation of these giant oolites showing similarities to those in the Neoproterozoic included:

(1) A high-energy environment developed on the shallow ramp under strong action of tidal and wave currents during the formation process of the ramp carbonate platform favorable to the formation of high-energy oolites (Simone, 1981; Flügel, 1982, 2004; Tucker and Wright, 1990; Mei et al., 1997; Siewers, 2003; Reeder and Rankey, 2008);
(2) Strong agitation of the depositional water bodies in the high-energy environment, which can result in frequent reworking of sedimentary grains on the sea floor, and thus be favorable to the generation of oolites (Simone, 1981; Flügel, 1982, 2004; Tucker and Wright, 1990; Mei et al., 1997; Siewers, 2003; Reeder and Rankey, 2008). The resultant oolites (e.g. Figs. 3 and 4) are representative of ooids of pelagic ('suspended') origin (Gerdes et al., 1994; Brehm et al., 2003, 2006);
(3) Remoteness from siliclastic sources (e.g. Fig. 1), which can generate clear water with few siliceous elements that is most conducive to the generation of oolites;
(4) The underlying strata of the top Daye Formation oolitic limestones at the Lichuan section are marked by aphanitic and laminated micritic limestones, which reflect low generation and provision rates of bioclasts, which in turn would have led to a concomitant low rate of ooid nucleuses.

As noted above, the observation of Neoproterozoic giant oolites (Summer and Grotzinger, 1993; Grotzinger and James, 2000) led to a change in concept so that the term "pisolite" that was traditionally used to refer to large oolites with a diameter of more than 2 mm has now been restricted to refer to the ooid-like non-marine carbonate grains formed by freshwater diagenesis. Ooids with a diameter of more than 2 mm have been defined consequently as those of a giant oolite (Siewers, 2003; Flügel, 2004). The giant Neoproterozoic oolites have the largest size with more than 14 mm, and most are 8—9 mm in diameter, which is instructive to consider variation in ooid size. For the Neoproterozoic examples, Summer and Grotzinger (1993) gave a reasonable interpretation for their origin, which included a combination of the following: 1) a higher growth rate due to higher carbonate saturation of seawater; 2) lower nucleation rate imparted by a low flux of nuclei; 3) increased storminess due to the prevalence of ramps and the possibly stormier weather in an erratic climate; 4) increased absolute level of storminess that was genetically related to the waxing and waning of the extensive Neoproterozoic ice sheet.

Considering that the giant Neoproterozoic oolites occur stratigraphically below tillite deposits formed during the glaciation (Swett and Knoll, 1989; Knoll and Swett, 1990) or between glacial periods (Singh, 1987), and that the giant oolites are absent in most similar settings of Phanerozoic age such as the Neogene icehouse, the increased agitation cannot be the sole catalyst for the development of giant oolites (Grotzinger and James, 2000). Although there are some uncertainties for the origin of the Neoproterozoic giant oolites, they do provide an important analogy for the further understanding of the Triassic giant oolites in the study area.

The formation age of the Triassic oolites at the Lichuan section during the last period of the Induan is just the time of recovery of biota after the end-Permian biological mass extinction (Schubert and Bottjier, 1992; Wignall and Twitchett, 1999; Pruss et al., 2004; Hips and Hass, 2006; Liu et al., 2007), which means that there are peculiarities in the sedimentary and environmental settings of this special time in the study area: 1) the development of vast epicontinental areas that were characterized by a low-angle carbonate ramp resulting from the breakup of Pangea (Santosh, 2010); 2) that ramp is dominated by neritic lime-mud deposition, along with peloids, ooids and minor amounts of bioclasts, equivalent to the skeleton-poor sea of the Early Cambrian (Pruss et al., 2010); 3) a special geological period that is dominated by sedimentation of microbial carbonates and respective deposits (Schubert and Bottjier, 1992; Wignall and Twitchett, 1999; Pruss et al., 2004; Hips and Hass, 2006; Kershaw et al., 2007; Liu et al., 2007; Mei, 2007), such as stromatolites (Schubert and Bottjier, 1992), unusual edgewise intraclasts (Wignall and Twitchett, 1999), and wrinkle structure (Pruss et al., 2004), indicating among other things the development of microbial mats on the depositional surface.

As seen in Fig. 2, the Daye Formation represents the development of a low-angle ramp platform with an area of more than one million square kilometers (Wu et al., 1994; Enos et al., 2005), in which a sedimentary setting that is favorable to the generation of oolites is developed. Given this setting, increased storminess due to the prevalence of ramps and possibly a stormier climate might have led to the development of the agitating water conditions needed for the generation of oolites; further, the development of a neritic lime-mud “factory” (Pomer and Hallock, 2008) in the recovery period after biological extinction could have led to low generation/provision rates of oolitic nucleuses conducive to the formation of the giant oolite. Thus, the formation environment of the Triassic oolites has many similarities to that of the giant Neoproterozoic oolites (Swett and Knoll, 1989; Knoll and Swett, 1990; Summer and Grotzinger, 1993; Grotzinger and James, 2000), including neritic lime-mud production, a marine environment with relatively high seawater alkalinity, low production rate of bioclasts, and the agitating environment. Ultimately, together with the special stromatolite and other microbial carbonates (Schubert and Bottjier, 1992; Hips and Hass, 2006; Kershaw et al., 2007; Mei, 2007), the unusual edgewise intraclasts (Wignall and Twitchett, 1999), the wrinkle structure indicating the development of microbial mats (Pruss et al., 2004) and so on, both the diversity of oolitic morphology and the development of an unusual giant oolite in the Phanerozoic in the study area reflect a devasted sea-floor environment (Schubert and Bottjier, 1992; Wignall and Twitchett, 1999; Fang, 2004; Pruss et al., 2004; Hips and Hass, 2006; Kershaw et al., 2007; Liu et al., 2007; Wu et al., 2007) or else a new kind of anachronistic facies (Pruss et al., 2004; Li et al., 2010) in the aftermath of the end-Permian mass extinction.

Although the origin of oolites remains uncertain, their morphological diversity with the development of an unusual giant oolite in the Phanerozoic provides an important example to help us understand more about the evolution of the carbonate world represented by giant oolites (Wu, 1992; Grotzinger and James, 2000; Flügel, 2004; Yan and Wu, 2006; Pomer and Hallock, 2008). Furthermore, this important example also provides an important clue to further research. Importantly, some of the microbial features for the Triassic giant oolite, as seen in Fig. 4, such as the relatively thick ooid rings composed of dark amorphous micrites enriched with organic substances and nucleuses made up of echinoderm bioclasts with reworking of microbial borings, may also represent a type of post-mass-extinction disaster form in addition to microbialites, edgewise intraclasts, wrinkle structures and so on. If so, they act as a proxy for a high-energy agitating skeleton-poor sea that is favorable to the formation of giant oolites directly or indirectly controlled by microbial activities.

6. Conclusions

Both the diversity of ooid morphology and the development of the oolitic grainstones in the top part of Lower Triassic Daye Formation at the Lichuan section, Hubei Province, not only provide an example of the development of unusual giant oolites in the Phanerozoic but also provide an important clue to study further evolving sedimentary response to biological mass extinction in the carbonate world. These oolitic limestones formed during a special geological period, i.e., the Induan, after the most severe biological mass extinction of the Phanerozoic, and in a special sedimentary setting, i.e., on a ramp carbonate platform after a major transgression, somehow similar to Neoproterozoic giant oolites. Although the natural formation conditions for a single ooid remains uncertain, the observations on the Triassic giant oolites in the study area also provide important clues toward understanding this conundrum of sedimentology, *i.e.*, the original mechanism of oolites.

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